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Abstract

Due to their finite lifetime, muons must be accelerated very rapidly. It is challenging to make the magnets ramp fast enough to accelerate in a synchrotron, and accelerating in a linac is very expensive. One can use a recirculating accelerator (like CEBAF), but one needs a different arc for each turn, and this limits the number of turns one can use to accelerate, and therefore requires significant amounts of RF to achieve the desired energy gain. An alternative method for muon acceleration is using a fixed field alternating gradient (FFAG) accelerator. Such an accelerator has a very large energy acceptance (a factor of two or three), allowing one to use the same arc with a magnetic field that is constant over time. Thus, one can in principle make as many turns as one can tolerate due to muon decay, therefore reducing the RF cost without increasing the arc cost. This paper reviews the current status of research into the design of FFAGs for muon acceleration. Several current designs are described and compared. General design considerations are also discussed.

INTRODUCTION

An FFAG accelerates muons using a single arc with magnets whose fields do not vary with time. The arc must be able to transmit a beam over a wide range of energies. The first difficulty encountered in designing such an arc is ensuring that there are no single-cell linear resonances in the energy range of interest. There are three ways of achieving this:

- The arc has a tune which is independent of energy. This is what occurs in the original conception of an FFAG [1], what we are here calling a "scaling FFAG." Other designs are referred to as "non-scaling FFAGs."
- The single-cell tune at the lowest energy is less than 0.5, and decreases as the energy increases [2].
- Have a single-cell tune above 0.5, and use sextupoles to control chromaticity and maximize the energy range determined by the linear resonances [3].

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Acceleration is generally achieved by distributing RF cavities relatively uniformly around the ring. Since the muons are decaying, acceleration must be rapid (generally on average at least 1 MV/m). This means that in non-scaling FFAGs, one accelerates rapidly through any nonlinear resonances, and thus these are of little concern. Acceleration is still sufficiently gradual, however, that the bunch will adiabatically follow the energy-dependent closed orbit in the machine.

Due to the rapid acceleration, it is impractical to restore energy to the cavities at the rate that the beam is extracting it, or to change the phase of the RF as the beam accelerates. Since no FFAG design is perfectly isochronous, there is the problem that the beam does not stay at the same phase of the RF from one turn to the next. The result is that there is a minimum installed RF voltage needed to accelerate over the desired energy range. For a given type of relationship between time-of-flight and energy, that minimum voltage is proportional to the difference between the minimum and maximum time-of-flight over the energy range [4]. In addition, the longitudinal phase space area transmitted increases as the voltage increases above that minimum voltage, or equivalently as the time-of-flight range decreases.

In general, reducing the cell length reduces both the time-of-flight range and the required magnet aperture, as does increasing the number of cells in the ring.

RF CAVITIES

One of the primary reasons for using an FFAG for acceleration is the reduction in RF costs. This is achieved by making many passes (10 to 20) through the same cavities.

In the US neutrino factory designs [5, 6], 201.25 MHz (or a multiple thereof) RF must be used for acceleration. One can use superconducting or room-temperature RF for this purpose. Either type of cavity must be run near its maximum gradient (12 MV/m or more) so that the voltage does not drop too much due to beam loading. This causes the costs of room-temperature RF to far exceed that of superconducting RF, due to the substantial peak power requirements for the former.

The disadvantage of superconducting RF is the need to maintain low magnetic fields on the superconducting surfaces of the cavities. This requires space to be placed between the magnets and the cavities that would not need to be there were room-temperature RF being used. Under normal circumstances, that field would need to be around 0.1 Gauss. However, if the cavities are cooled down before the magnets are powered, that field can be as high as 0.1 T [7]. There is little danger of inadvertent quenching, since 200 MHz cavities are made of Niobium sputtered on copper, and the volume of copper will prevent the quenching [8].

Preliminary studies have indicated that 50 cm is a sufficient cavity-magnet distance to bring the fields down to the desired levels. Thus, 200 Mhz cavities will require a roughly 2 m drift, whereas room-temperature cavities would only require around 1 m.

For the NufactJ scaling FFAG designs [9], lower frequency RF is required. Due to their low frequency, they have a large amount of stored energy. Relatively high gradients for that frequency are required. Due to the extremely low duty factor for the power sources, the large amount of peak power should be relatively inexpensive.

SCALING FFAGS

Scaling FFAGs are the only type of FFAGs that have ever been built [10, 11, 12]. A neutrino factory design using scaling FFAGs has been produced by the NufactJ working group [9]. The design has no cooling, and uses four successive FFAG rings to reach an energy of 20 GeV.

The design uses 24 MHz RF (other frequencies in this range may also be used). An RF bucket is created which encompasses both the initial and final energies for the acceleration stage, and the bunch undergoes half a synchrotron oscillation in that bucket to get from the lowest to highest energy. There has also been preliminary success with a scheme using something resembling two RF buckets, one accelerating from the lowest energy to an intermediate energy, then the second accelerating to the final energy [13].

In a scaling FFAG, the midplane vertical magnetic field is of the form $B_{y0}(\theta)(r/r_0)^k$, where r and θ are cylindrical coordinates centered at the center of the ring, and r_0 is a reference radius. As k increases, the dispersion decreases, reducing the required magnet aperture. The time-of-flight range also decreases with increasing k. Thus, maximizing k seems to be advantageous. The difficulty with this is that for larger k, the fields become more nonlinear, and the dynamic aperture becomes reduced.

Preliminary designs for superconducting magnets for the highest energy accelerator (10—20 GeV) have been made. They use a $\cos\theta$ style of design (with an elliptical vacuum chamber), but the coils are distributed highly asymmetrically to give the r^k field dependence. In addition, a trim coil has been included to allow the adjustment of k over a limited range [14].

NON-SCALING FFAGS

There has been work on a number of non-scaling lattice designs. These all share the common property that their time-of-flight varies parabolically as a function of energy. The lattices are tuned so that the minimum of that parabola is placed at the central energy, so as to minimize the time-of-flight range.

Low Emittance Lattice

This lattice is based on a lattice cell which would give a low emittance for an electron ring [3]. Both the dispersion and beta functions are small at the bending magnet. The primary appeal is that the closed orbit variation and the time-of-flight range are small. These properties allow the ring to be made relatively short. Such a ring seems to be very inexpensive.

Unfortunately, this lattice has a very poor dynamic aperture due to the sextupoles required to control the chromaticity in this lattice, since its tune is above 0.5.

FODO Lattice

The original non-scaling FFAG design was based on a FODO lattice [2]. The lattice consists of two gradient dipoles with drifts between them. A simple procedure has been developed to design these lattices using standard nonlinear minimization and/or equation solving algorithms: vary the lattice parameters so that the frequency slip factor at the central energy is zero and the tunes at the minimum energy are some fixed value below 0.5. There are degrees of freedom remaining to optimize costs or insure that the lattice meets certain minimum requirements, such as a maximum amount of decay, a maximum number of turns (beam loading considerations), maximum pole tip fields, or a minimum longitudinal acceptance. These techniques have been used to demonstrate various properties of the lattice such as

- The time-of-flight range is linear in the cell length. The drifts should therefore have the minimum length compatible with the space requirements for cavities.
- The time-of-flight range is roughly inversely proportional to the number of cells.
- The time-of-flight range decreases as the minimum tune increases, but at the cost of an increasing beta function at low energy. The former decreases the cost, while the latter will increase costs.

The ability to generate these lattices automatically and rapidly has become a useful tool in performing cost optimizations and comparisons.

Triplet Lattice

The triplet lattice has arisen as a candidate lattice from two directions. Since the dynamic aperture of the low-emittance lattice was so poor, the sextupoles were removed. The tune needed to be brought below 0.5 for this lattice to work, and so a pair of quadrupoles was removed, leaving the triplet lattice. From the other direction, the two long drifts in the FODO lattice were often unnecessary, so making a lattice cell with with only one drift seemed logical.

Table 1: Accelerating system costs for various designs.

	Range GeV	# Cells	Voltage GV	Magnet Cost	RF Cost	Other Costs	Total Cost	Per GeV
Study-II RLA	2.5–20	218	4.38	63	263	58	384	21.9
Scaling	10–20	180	1.26	178	89	32	299	29.9
FODO	10–20	108	0.91	54	55	15	124	12.4
Triplet	10–20	89	0.8	28	48	12	87	8.7
Triplet	5–10	70	0.47	30	28	8	66	13.2
Triplet	2.5–5	58	0.19	25	39	3	67	26.8

The triplet lattice is designed just as the FODO lattice is: all three magnets are combined-function magnets, the frequency slip factor at the central energy is set to zero, and the tunes at the minimum energy are set to values somewhere below 0.5. For a given drift length, the triplet lattice seems to have a lower time-of-flight range.

Racetrack

Any of these lattices can be used to create an even lower time-of-flight range as a function of energy by using a racetrack configuration. The RF is placed in the straights, where there is almost no time-of-flight variation with energy. Time-of-flight range in the arcs is minimized by minimizing the drift space: none is needed for the RF. Adiabatic transitions are made between the arcs and the straights. The greatest difficulty is in the adiabatic transitions; some preliminary work has been done [15].

COST ANALYSIS

Starting with approximate cost formulas for magnets and RF cavities, we have attempted to compare the costs of various designs. Table 1 summarizes these comparisons. Note that the triplet lattices are the result of inexact attempts at optimizing the lattice cost (the lattice costed is not a lattice that was actually designed), but are expected to be a good reflection of the actual cost trend.

The increased magnet cost in the scaling lattice over the FODO lattice results from the larger number of cells required and the fact that the defocusing quadrupole in the FODO lattice has a smaller aperture than the corresponding quad in the scaling lattice (the focusing quads have similar aperture). Furthermore a larger RF voltage is required in the scaling lattice, thus increasing the RF costs. Improving the performance of the scaling lattice would require increasing the k, or maybe even *increasing* the number of cells (thus reducing the apertures and maybe lowering the RF requirements).

The triplet lattice appear to be more cost effective than the FODO lattice, but this may be deceptive, since different attempts at optimization have been performed on the triplet lattice than on the FODO lattice. A more systematic comparison needs to be performed.

Note the incrased cost per GeV as the energy range of the FFAG is lowered. This largely results from larger aperture requirements at the lower energies. The increased RF costs in the lowest energy range result from the need to reduce the drift in that lattice, and thus use room-temperature instead of superconducting RF.

Finally, note that the costs of the triplet lattices were minimized by choosing a larger number of cells that what was initially thought necessary, and by using relatively modest superconducting pole-tip fields (around 4 T). Larger pole tip fields drive up the magnet cost rapidly, and the larger apertures required for a short ring (due to dispersion) also drive up the cost significantly.

REFERENCES

[1] K. R. Symon *et al.*, Phys. Rev. **103**, 1837 (1956).

[2] C. Johnstone and S. Koscielniak, in *Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001)*, ed. N. Graf, SNOWMASS-2001-T508.

[3] D. Trbojevic *et al.*, in *Proceedings of EPAC 2002, Paris, France* (EPS-IGA/CERN, Geneva, 2002), p. 1199.

[4] J. S. Berg, in in *Proceedings of EPAC 2002, Paris, France* (EPS-IGA/CERN, Geneva, 2002), p. 1124.

[5] N. Holtkamp and D. Finley, eds., Fermiab-Pub-00/180-E (2000).

[6] S. Ozaki *et al.*, BNL-52623 (2001).

[7] M. Ono *et al.*, in *9th Workshiop on RF Superconductivity 1999* (Los Alamos, NM, 2002), Los Alamos National Laboratory report LA-13782-C.

[8] Hasan Padamsee, private communication.

[9] NufactJ Working Group, "A Feasibility Study of a Neutrino Factory in Japan," http://www-prism.kek.jp/nufactj/ (2001).

[10] F. T. Cole *et al.*, Rev. Sci. Instrum. **28**, 403 (1957).

[11] D. W. Kerst *et al.*, Rev. Sci. Instrum. **31**, 1076 (1960).

[12] M. Aiba *et al.*, in *Proceedings of EPAC 2000, Vienna, Austria*, p. 581.

[13] T. Uesugi and C. Ohmori, presentations given at the Neutrino Factory and Muon Collider Colaboration Workshiop on FFAG Acceleration, Berkeley, CA, Oct. 28–Nov. 8, 2002.

[14] T. Ogitsu, presentation given at the Neutrino Factory and Muon Collider Colaboration Workshiop on FFAG Acceleration, Berkeley, CA, Oct. 28–Nov. 8, 2002.

[15] Eberhard Keil, unpublished note, http://keil.home.cern.ch /keil/MuMu/Doc/FFAG02/adiabatic.pdf (2002).